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THE LONG-TERM INTENSITY BEHAVIOR OF CENTAURUS X-3

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ABSTRACT

In 3 years of observation from *Uhuru* (1970 December–1973 June), the X-ray source Cen X-3 appears to alternate between "high states," with an intensity of 150 counts s^{-1} (2–6 keV) or greater, and "low states" where the source is barely detectable. The time scale of this behavior is of the order of months, and no apparent periodicity has been observed.

The analysis of two transitions between these states is reported. In particular, during 2 weeks in 1972 July, the source increased from about 20 counts s^{-1} (2–6 keV) to 150 counts s^{-1}. The detailed nature of this turn-on, including orbital phase, spectral variation, and fractional power pulsed is interpreted in terms of a model in which the supergiant's stellar wind decreases in density. A second transition, a turnoff in 1973 February, is similarly analyzed and found to be consistent with a simple decrease in accretion rate. The presence of absorption dips during transitions at orbital phases 0.4–0.5 as well as at phase 0.75 is discussed. Analysis of data from extended lows shows the persistence of the 2 day binary period with the intensity varying from 4.6 ± 1.1 counts s^{-1} to 10.7 ± 1.1 counts s^{-1} (2–6 keV).

The data are consistent with a stellar wind accretion model and with different kinds of extended lows caused by increased wind density masking the X-ray emission or by decreased wind density lowering the accretion rate.

Subject headings: stars: binaries — stars: winds — X-rays: sources

I. INTRODUCTION

The X-ray source Cen X-3 is one of two known binary X-ray pulsars. Both Cen X-3 and Her X-1 are generally taken to be compact objects—most likely magnetic rotating neutron stars—accreting matter from close companions. They both show regular pulsations with $4^{s}.8$ and $1^{s}.2$ periods, respectively, and well-defined eclipsing light curves, with $2^{d}.1$ and $1^{d}.7$ periods, respectively (Giacconi *et al.* 1971; Schreier *et al.* 1972; Tananbaum *et al.* 1972). They also both show longer time scale variability. Her X-1 has a fairly regular 35 day cycle of OFF and ON states, while Cen X-3 has been reported to undergo less well-defined extended lows, where the source remains at an intensity comparable with eclipse level for long periods of time. The extended lows of Cen X-3 were noted in the early *Uhuru* data (Schreier *et al.* 1972), have been seen by OSO-7 (Baity *et al.* 1974), and may explain some of the variability seen in early rocket observations of the source (e.g., Margon *et al.* 1972; and references quoted in Schreier *et al.* 1972).

In this paper, we present a study of certain *Uhuru* observations of Cen X-3 concerning the long-term behavior of the source. In particular, we show the detailed nature of the transitions between the low and high states, and discuss the implications for the nature of the mass transfer from the companion star.

II. OBSERVATIONS

The early *Uhuru* data showed no evidence for any periodicity in the extended lows of Cen X-3. In an effort to search further for any long-term regularities of Cen X-3's extended low behavior, we have attempted to categorize all *Uhuru* observations of the source as either high or low intensity, without performing any detailed aspect corrections. Figure 1 shows the *Uhuru* data which we have scanned for this quick-look survey, ranging from launch in 1970 December through 1973 June. The typical "high state" represents an intensity of 150 counts s^{-1} (2–6 keV) or greater, with obvious $4^{s}.8$ pulsations present. The typical low state represents intensities of 15 to 20 counts s^{-1} or less, at times when the extrapolated binary phase predicts a higher intensity. It is apparent from this overview that no regular cycle of highs and lows is followed. Furthermore, the duration of any given high state or low state cannot be predicted. Typical low states can last from about 2 weeks to 2 months; similarly, high states seem to last from 1 month to as much as 4 months.

However, as indicated in Figure 1, a third category of long-term intensity behavior was found; the source appeared to be between the high and low intensity states. Since these states, as well as contiguous lows and highs, apparently represent transitions between

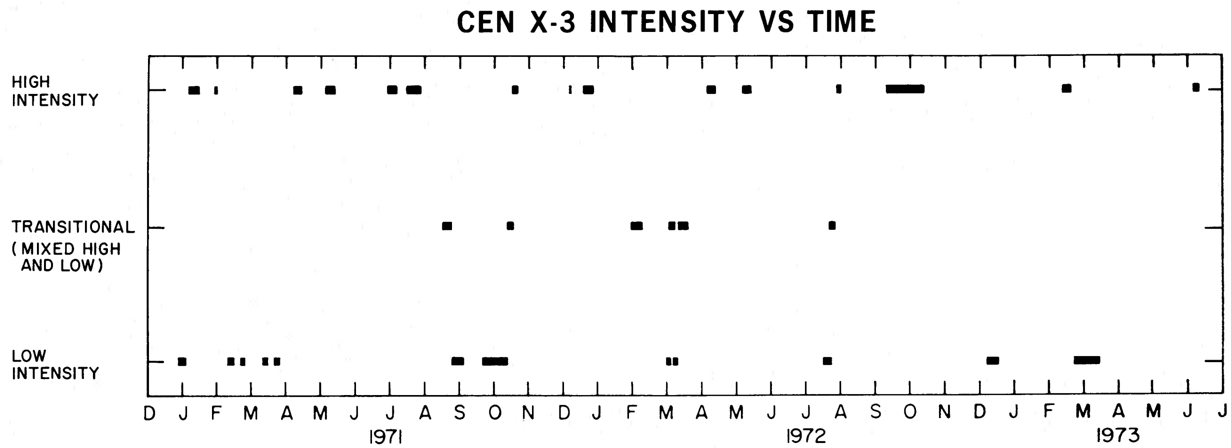

FIG. 1.—The long-term 2–6 keV intensity behavior of Cen X-3 as seen by *Uhuru* from 1970 December to 1973 June. The sightings were divided into high, transitional, and low; high indicates an intensity of 150 counts s^{-1} (2–6 keV) or greater, low indicates 15 to 20 counts s^{-1} (2–6 keV) or less.

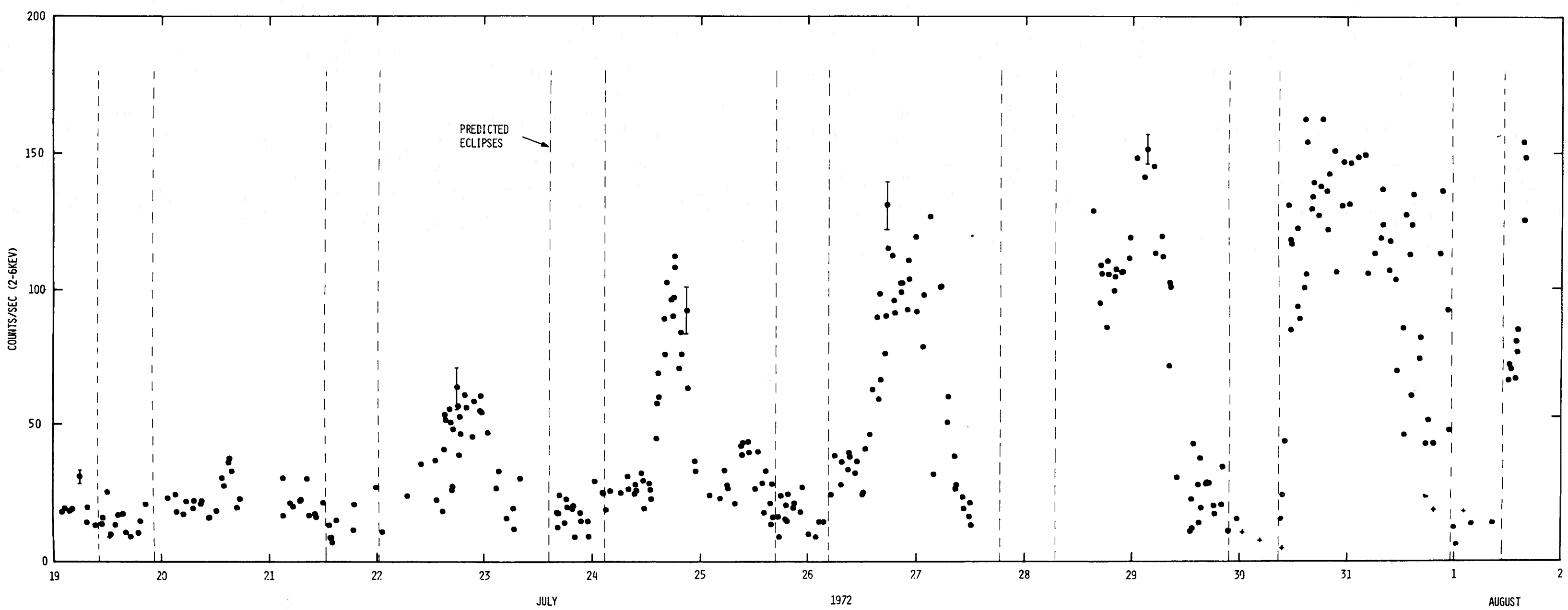

FIG. 2.—Cen X-3 light curve in 1972 July. Each point represents the average intensity (2–6 keV) over 20 s, with background subtracted, corrected for elevation in the field of view of the collimator. Typical 1 σ error bars include counting statistics and aspect correction errors. The predicted eclipse phases are extrapolated from fits to the pulsation phase changes (Schreier *et al.* 1972). The gap in coverage during July 27.5–28.5 is due to loss of pointing. The points indicated by + signs are 2 σ upper limits.

high and low states, it was decided to study them in more detail. In particular, one transition from low to high state in 1972 July and one transition from high to low state in 1973 February were studied. A second possible low-to-high transition in 1972 March was also studied.

During 1972 July, *Uhuru* observed Cen X-3 for 14 days. All of the available 20 s sightings from *Uhuru*'s 5° full width at half-maximum (FWHM) collimator are shown in Figure 2. Each of the approximately 350 points represents the 2–6 keV intensity, averaged over the 20 s sighting and corrected for elevation in the field of view of the collimator. Typical 1 σ errors including both counting statistics and possible systematic aspect correction errors are shown. The coverage is fairly uniform except for a 1 day gap due to lack of pointing. It should be noted that the 15 counts s^{-1} intensity at the beginning of the 14 day interval is typical of both the eclipse level and what had been taken to be the extended low level (cf. Schreier *et al.* 1972). Furthermore, the light curve over the last 2 days is typical of a normal high state. Data from the $0\overset{\circ}{.}5$ FWHM collimator were used to confirm that the light curve was not significantly contaminated by nearby sources (3U 1134−61 at 9 counts s^{-1} and 3U 1145−61, a variable source, ranging from 15 to 72 counts s^{-1} [Giacconi *et al.* 1974]).

The qualitative features of the turn-on, as reflected in the 2–6 keV flux, can be summarized simply. The intensity first increases in a time interval centered near orbital phase 0.5 and lasting between $0\overset{d}{.}4$ and $0\overset{d}{.}7$. The intensity near phase 0.5 increases over several orbital periods by a factor of 3 or 4, while the intensity near phase 0.25 and 0.75 increases by less than 50 percent, consistent with no increase. Although the statistical and aspect errors do not permit a very quantitative discussion of this phenomenon, the data near phase 0.5 can be described as a spike with a width significantly smaller than the entire non-eclipsed portion of the orbital period. In the third period shown in Figure 2, for example, the intensity increases from 25 counts s^{-1} to 100 counts s^{-1} in less than 2 hours; the FWHM of the feature is approximately 5 hours. After the third period, the spike is seen to increase in width as well as in intensity, until it finally fills all or most of the interval between phases 0.12 and 0.88 as in the "normal" high state. It should also be noted that in the last complete orbital period observed there is a significant scatter of points between phases 0.65 and 0.80. This feature, reminiscent of the "dips" of Her X-1 (Giacconi *et al.* 1973), will be discussed below.

In order to gain a better understanding of the turn-on, we also analyzed the energy spectral data available. We used the data from the narrow *Uhuru* collimator ($0\overset{\circ}{.}5$ FWHM) with seven energy channels from 2–20 keV. The results from spectral fitting to an exponential with low-energy cutoff are contained in Table 1. The noneclipse data for the first five orbital periods have been divided into three parts: "pre-spike," "spike," and "post-spike." For the first two periods, since the intensity variation with phase was not sharply defined, the noneclipse time was simply divided in thirds. The next three periods, however, contained data of sufficient statistical significance to actually define the beginning and end of the spike, as indicated by the

TABLE 1

2–20 keV DATA FIT TO $\exp\{-(E_a/E)^{8/3} - (E/kT)\}$

Orbital Cycle	Pre-Spike	Spike	Post-Spike
I and II.	$kT \geq 3$ keV $E_a = 2.8\,(+1.2, -1.8)$ keV $I = 20 \pm 1$ (3)* counts s^{-1} ϕ 0.12–0.37 (phase)	$kT \geq 5$ $E_a = 2.5 \pm 1.0$ $I = 30 \pm 2$ (7)/48 $\pm$ 7 (13)† ϕ 0.37–0.63	$kT \geq 4$ $E_a = 2\,(+1, -2)$ $I = 15 \pm 1$ (7)/23 $\pm$ 4 (9)† ϕ 0.63–0.88
III.	$kT \geq 5$ $E_a = 3.5\,(+1.0, -0.5)$ $I = 27 \pm 2$ (4) ϕ 0.12–0.30	$kT \geq 15$ $E_a = 2.5 \pm 0.5$ $I = 77 \pm 6$ (23) ϕ 0.30–0.58	$kT \geq 25$ $E_a = 4.0 \pm 0.5$ $I = 29 \pm 2$ (10) ϕ 0.58–0.88
IV.	$kT \geq 19$ $E_a = 2.6 \pm 1.5$ $I = 33 \pm 3$ (6) ϕ 0.12–0.30	$kT \geq 20$ $E_a = 2.5 \pm 0.4$ $I = 85 \pm 5$ (29) ϕ 0.30–0.66	$kT \geq 24$ $E_a = 3.3\,(+0.5, -1.0)$ $I = 23 \pm 1$ (8) ϕ 0.66–0.88
V.	No data	$kT \geq 25$ $E_a = 2.0 \pm 0.2$ $I = 112 \pm 4$ (20) ϕ 0.25–0.66	$kT \geq 25$ $E_a = 4.0 \pm 0.5$ $I = 25 \pm 2$ (10) ϕ 0.66–0.88

Orbital Cycle	Transition	High	Dip	Transition
VI.	$kT \geq 15$ $E_a = 2.8 \pm 0.2$ $I = 106 \pm 5$ (30) ϕ 0.12–0.22	$kT \geq 16$ $E_a = 2.0 \pm 0.2$ $I = 132 \pm 8$ (16) ϕ 0.22–0.63	$kT \geq 7$ $E_a = 3.8\,(+0.2, -0.4)$ $I = 73 \pm 6$ (39) ϕ 0.63–0.82	$kT \geq 14$ $E_a = 2.5 \pm 0.4$ $I = 97 \pm 10$ (37) ϕ 0.82–0.88

* Numbers in parentheses indicate rms deviation of data.

† Cycles I and II separately.

phase entries in Table 1. The noneclipsed portion of Period VI was divided into four parts, defined qualitatively as a period of transition between eclipse level and high state, a high state, a "dip" region containing intermixed high- and low-intensity points between phase 0.63 and 0.82, and a final "transition" containing the final points before eclipse.

The error bars were determined from the two-dimensional chi-square contours for an $\{E_a, kT\}$ grid. In particular, the maximum extent of the contour $\chi^2 = \chi^2_{\min} + \chi_p^2(\alpha)$ was used to estimate $\pm 1\ \sigma$ values for each parameter, where $\chi^2_{\min}$ = minimum value of χ^2, and $\chi_p^2(\alpha)$ is the tabulated χ^2 value for p degrees of freedom and probability α (see Margon *et al.* 1975). For the current analysis, $p = 3$, the number of free parameters, and α corresponds to 1 σ probability.

The statistics for the first two periods do not allow significant conclusions. For the next three cycles, it is clear that the post-spike observations show significantly higher low-energy cutoff than the central observations —3.8 ± 0.4 versus 2.2 ± 0.2. Furthermore, the pre-spike data are also consistent with a higher cutoff of 3.2 ± 0.9 keV. In the sixth period, it can be seen that the transitions into and out of eclipse have higher cutoffs on the average than the emission at phase 0.5, in qualitative agreement with normal high states (Giacconi *et al.* 1971). But the "dip" region has a cutoff of 3.8 keV, comparable with the highest cutoffs ever observed for Cen X-3. The dip region also has a possibly softer spectrum with an exponential lower limit of 7 keV, while we have temperatures during the other noneclipsed observations of greater than 15 to 20 keV. In the eclipse regions, a superposition of the data gives a significantly softer spectrum with a temperature of about 3(+7, −1) keV.

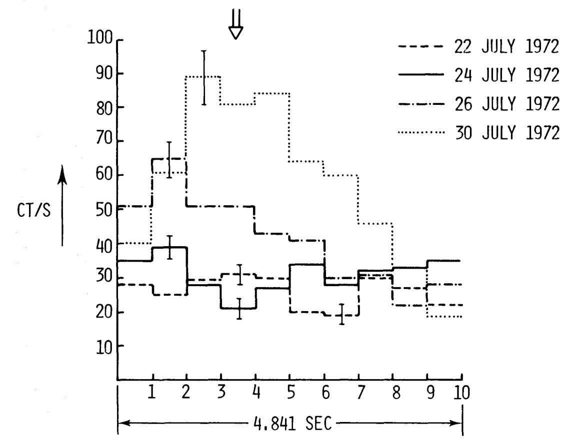

FIG. 3.—Data (2–6 keV) folded modulo the 4ˢ8 pulsation period. Several 20 s passes from each of four separate orbital periods during the 1972 July transition were phased together; each pass was corrected for heliocentric and binary orbit phase variations. The arrow indicates the phase of the fundamental 4ˢ841 sine curve fit to all of the data of the last full orbit.

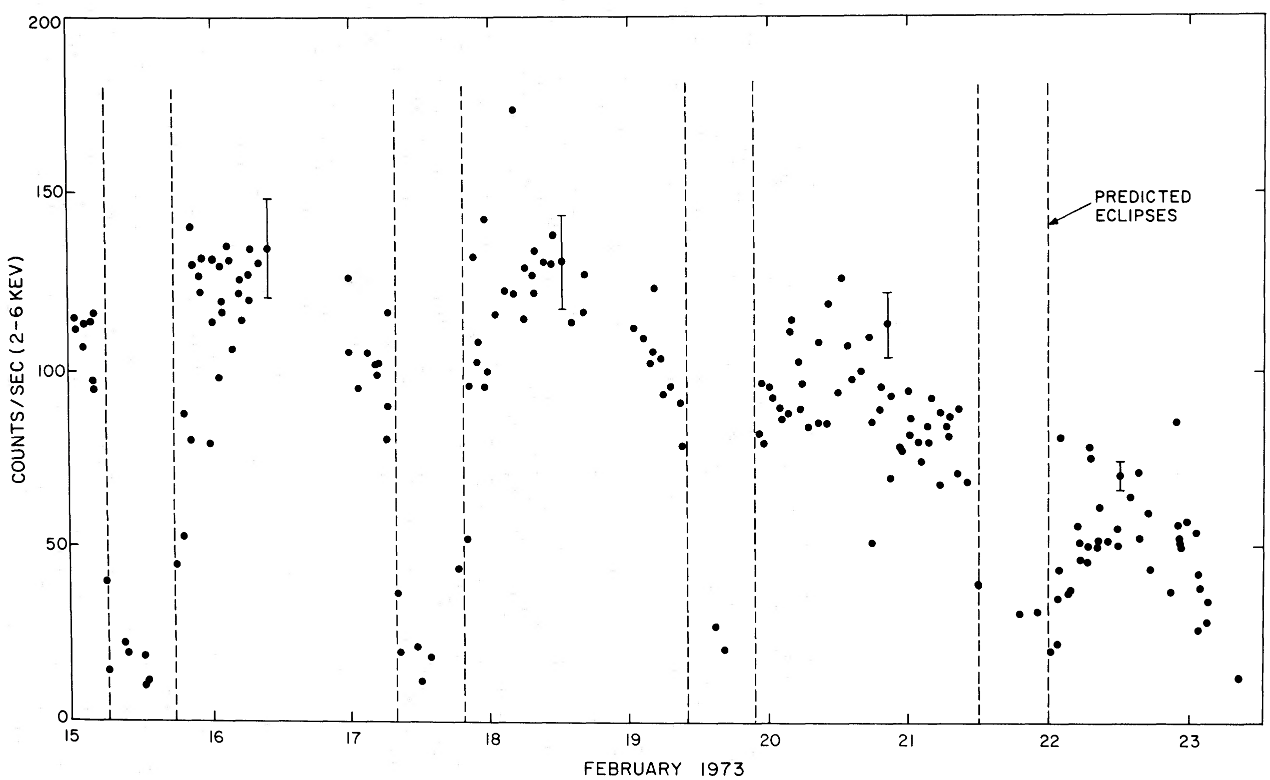

FIG. 4.—Cen X-3 light curve in 1973 February. See comments for Fig. 2.

We further attempted to study the 48 pulsations during the transition. The period and phase of the pulsations during the last full orbital cycle were determined using a phasing analysis technique (Schreier *et al.* 1972). Several individual 20 s sightings during each of the "spike" regions were separately folded together using the period and phase with appropriate orbital and heliocentric corrections; background, including an estimate of that due to the nearby sources, has been subtracted. The results of these foldings are shown in Figure 3. The arrows represent the predicted time of the peak of the fundamental sine curve; it should be noted that these tend to trail the actual peak intensity because of the presence of the strong first harmonic which produces the characteristic sharp rise and slow fall of the Cen X-3 pulse shape. It can be seen that the percentage pulsed power is definitely increasing as the source comes out of the extended low. Furthermore, there is some indication of a gradually changing pulse shape.

Another technique was used to quantify the fractional power pulsed (Joss 1974). Each 20 s pass was fitted with a sinusoidal function consisting of the fundamental period and one or more harmonics; the number of harmonics was chosen to minimize chi-squares per degree of freedom. The minimum value of the fitted function divided by the average intensity was then taken to be the nonpulsed fraction. In each of the first two orbital periods, the data are consistent with a value of 43 ± 5 percent power pulsed. The power pulsed in the succeeding four cycles are, respectively, 44 ± 3 percent, 57 ± 2 percent, 68 ± 5 percent, and 75 ± 8 percent, in qualitative agreement with the folded data in Figure 3. The reason for adopting this technique is that the pulse shape of Cen X-3 shows some variability as evidenced by the gradually changing average shapes in Figure 3 and by more rapid changes in other data (see below). Thus, folding data before fitting tends to broaden features and reduce power pulsed. A systematic study of the pulse variability is currently under way.

The second transition which has been studied is a turnoff in 1973 February. Cen X-3 was observed for approximately 1 week; the light curve obtained from the 5° FWHM collimator sightings is shown in Figure 4. The gradual decrease in intensity is apparent. Further observations approximately 2 weeks later show that the decrease continued. The data appear qualitatively different from a mirror image of the 1972 July turn-on. The most striking difference is the absence of any spikiness in the light curve. There are also no systematic spectral changes in evidence. All of the noneclipse data are consistent with an exponential spectrum with $kT \geq 16$ keV and a low-energy cutoff of $E_a = 2.2 \pm 0.2$ keV. The $4^{s}8$ pulse shape is found to be highly variable from pass to pass, with strong first and second harmonic components ($2^{s}4$ and $1^{s}6$) often present. There is no systematic pattern to the variability.

The fractional power pulsed during the first three

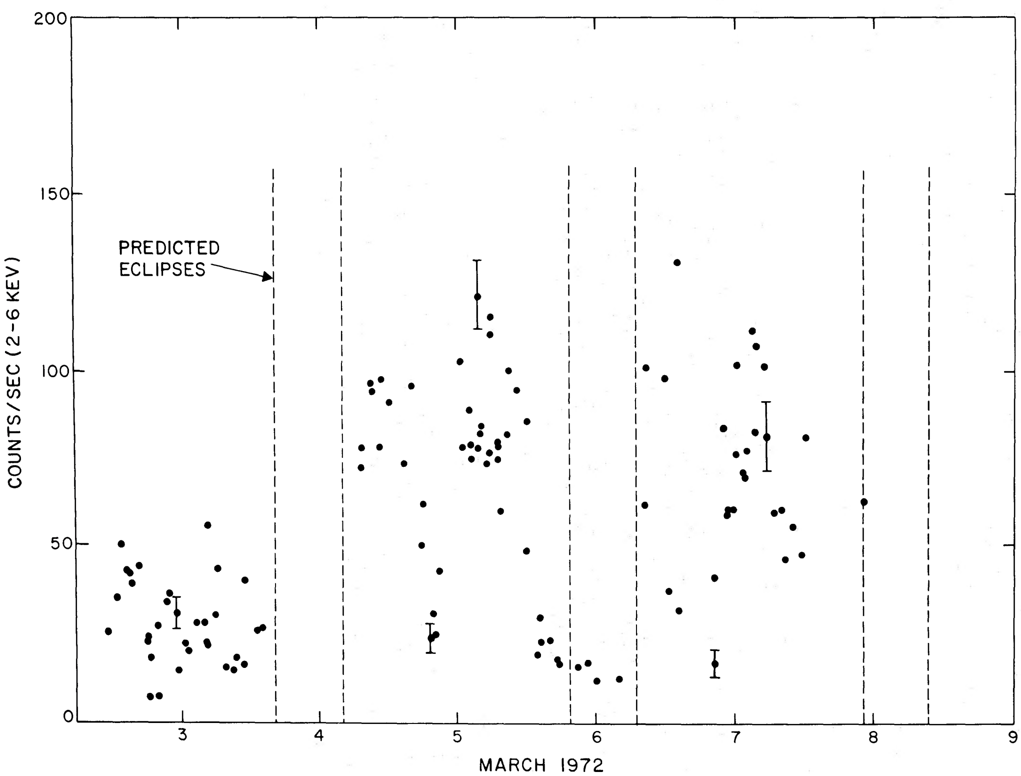

FIG. 5.—Cen X-3 light curve in 1972 March. See comments for Fig. 2.

orbital cycles was determined to be 47 $\pm$ 2 percent, with no evidence for any systematic change. In the last orbit, there is some indication of an increase in power pulsed. The nature of the variability of the pulse shape and its relation to the fractional power pulsed is currently being investigated further.

The behavior of Cen X-3 during the week of observations in 1972 March is shown in Figure 5. The source is seen to increase in intensity from the first to the second cycle, but not in the third. Noncontiguous data several days later are consistent with the intensity of the second and third cycles. Apparent in the light curve are intensity dips occurring between phase 0.4 and 0.5 in the second and third cycles; there is also evidence for a similarly phased dip in the later data. Although other dips have been observed in Cen X-3 light curves—e.g., in the *Uhuru* 1972 July data discussed above and in *Ariel-5* data from late 1974 (Pounds *et al.* 1974)—these have always occurred at phases 0.5 to 0.8 and not before phase 0.5.

Spectral analysis of the dips shows an exponential with $kT \geq 13$ keV and low-energy cutoff of 2.8 $\pm$ 0.1 keV. The spectra of the nondip points in the second and third cycles are consistent with $kT \geq 18$ keV and a cutoff of 1.9 $\pm$ 0.1 keV. However, the first cycle shows a significantly higher cutoff of 3.0 $\pm$ 0.2 keV. Thus, both the dips and the low-intensity first cycle are more cutoff than the nondip second and third cycles.

The Cen X-3 emission in the 1972 March data appears to be mainly double-pulsed ($2^{\mathrm{s}}4$). The fractional power pulsed in the first three cycles is consistent with 59 $\pm$ 3 percent. As with the 1973 February transition, there is no evidence for systematic change.

A final related study has further implications for the nature of the extended low. We considered extended low state observations on 1971 January 1, February 11–13, March 13–15, and March 21–22, all of the *Uhuru* data where star sensor data allowed detailed aspect corrections, and the satellite orientation allowed eliminations of source confusion. The binary orbital period was extrapolated, and 62 1 s sightings were found between phases 0.12 and 0.88, and 28 1 s sightings were found during predicted eclipses. Superpositions of these data allowed the determination of an eclipse intensity of 4.6 $\pm$ 1.1 counts s^{-1} and a noneclipse intensity of 10.7 $\pm$ 1.1 counts s^{-1}. We thus conclude that the 2 day periodicity did not disappear during these extended lows. It should be noted that the extended low eclipse intensity is significantly lower than the "normal" eclipse intensity of about 15 counts s^{-1}. This suggests that the eclipse level is related to the noneclipse intensity, and is not due to a nearby unresolved steady source. The spectral data during the extended low noneclipsed data shows $kT \geq 10$ keV and a cutoff less than 3 keV. It should, however, be noted that most of the extended low observations are close together in time; only the January 1 observations are separated from the others by known high states. Thus, if more than one kind of extended low state exists, as is suggested below, the above comments may be biased toward only one type.

III. DISCUSSION

Although Cen X-3 and Her X-1 display a remarkable similarity as X-ray pulsars in binary systems, it was clear from the start that there were important differences. The mass functions determined from their pulsation Doppler curves were 15 $M_\odot$ and 0.85 $M_\odot$, respectively, indicating significant differences between the masses of the two companion objects. This was confirmed by the optical identifications; Her X-1 is associated with a low mass, late A-type star HZ Her (Forman *et al.* 1972; Bahcall and Bahcall 1972; Davidsen *et al.* 1972), and Cen X-3 was identified by Krzeminski with a high mass O–B type supergiant (Krzeminski 1974; Rickard 1974). In fact the two systems appear to belong to stellar systems with very different evolutions (Gursky and Schreier 1974). Given the differences between the two companion objects, it is not surprising that the means of mass transfer are also different. Her X-1 has been considered as a canonical example of a Roche lobe mass transfer binary (e.g., Pines *et al.* 1972), and a strong case can now be made for the stellar wind as the means of mass transfer in Cen X-3.

The most direct evidence for a stellar wind in the Cen X-3 system has thus far come from spectroscopic observations of Krzeminski's star (e.g., Vidal *et al.* 1974). Further support has come from general evolutionary considerations (e.g., Van den Heuvel and Heise 1972). The published X-ray data (e.g., Schreier *et al.* 1972) showing gradual eclipse transitions, persistence of emission during eclipses, and existence of extended lows suggested an extended atmosphere and the presence of circumbinary material. However, the data presented in this paper, especially that concerning the transition of 1972 July, provide much stronger direct evidence in X-rays for the correctness of the idea; a simple consistent model can be constructed which explains the transition in a semi-quantitative way.

The basic observational features of the transition to be explained are as follows: (1) the source is first seen stronger at phase 0.5; (2) the intensity at phase 0.5 steadily increases, but the low-energy absorption does not change by a large amount; (3) the low-energy cutoff at the "shoulders," near phase 0.25 and 0.75, is significantly higher than at phase 0.5; (4) the pulsed fraction increases during the transition. These features are explained by considering the effect of the X-ray flux on a decreasing stellar wind density. As pointed out by various authors (Pringle 1973; McCray 1974), the X-ray flux is sufficient to fully ionize large regions of the stellar atmosphere. Pringle defined an ionized region bounded by a "Stromgren surface" such that the number of recombinations along any radius vector equals the number of ionizing photons. Using the parameters suggested by Davidson and Ostriker (1973) in their stellar wind accretion model to obtain a Cen X-3 luminosity of 10^{37} ergs s^{-1}—namely, a density n_e at the neutron star of 10^{11} cm^{-3}, an efficiency of 10^{-3}, and a wind velocity of 10^3 km s^{-1}—he showed that the flux from the X-ray source could

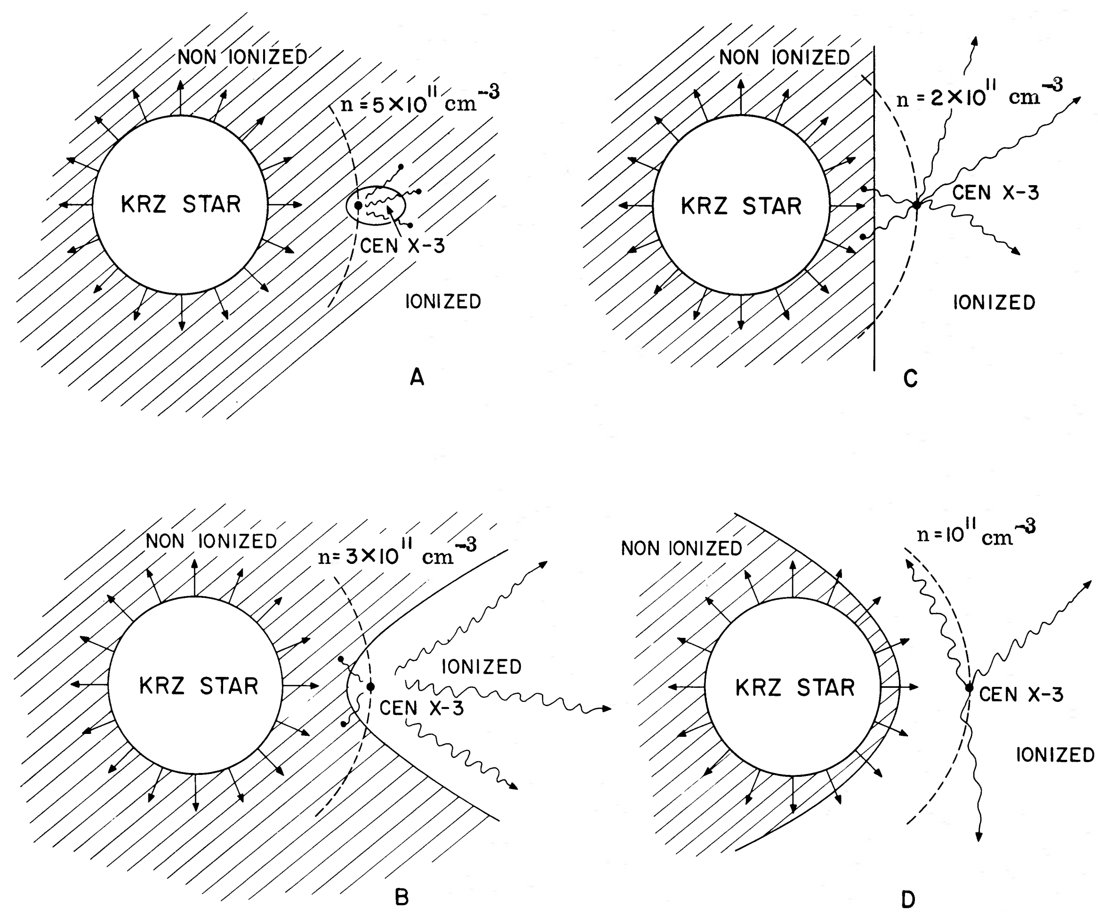

FIG. 6.—A representation of the 1972 July turn-on of Cen X-3. Part A shows the extended low with the source "buried" in the stellar wind. Parts B and C show the appearance and progressive widening of the "spike" near phase 0.5. Part D shows the normal high state, with a wind density at the neutron star of 10^{11} cm^{-3}. *Note.*—The other densities have been changed from the earlier calculation in Giacconi (1974) based on a forty-fold increase in wind density necessary to bury the source as opposed to our current estimate of a factor of 5.

reach us with little or no photoelectric absorption over some 280° (through the ionized gas) and suffer considerable absorption in the remaining 80° by the nonionized portion of the wind. The point of Pringle's discussion was to express concern about adopting the size of the nonionized occulting region as the size of the companion star.

As discussed by Giacconi (1974), we have estimated the "Stromgren surfaces" that would result in the event that the density of the wind was increased from the value n_e adopted by Davidson and Ostriker of 10^{11} cm^{-3}, using the formulas given by them for mass accretion rate, density dependence on R, etc., and requiring that L_x remain constant in the 2–6 keV range. This last condition decreases the factor by which density must vary to achieve transitions between ON and OFF states.

As shown in Figure 6 (Giacconi 1974), as the density increases the cone containing the ionized gas becomes progressively narrower until the "Stromgren surface" completely encloses the X-ray source. This occurs at a density of about $5n_e$. (Note that the numbers in Fig. 6 were changed from an early estimate in Giacconi 1974 of a forty-fold increase in density.) This, then, as Pringle had in fact suggested, provides a plausible explanation for the OFF periods of Cen X-3; namely, that the density in the stellar wind becomes so large that it can block the X-ray source, at least in the 2 to 6 keV range, presumably shifting the radiation to long wavelengths.

A turn-on would then be due to a decrease in density which allows the X-rays to ionize enough of the cold gas and become visible to us. This simple explanation appears to satisfactorily describe the detailed appearance and spectral content of the observed turn-on event. If we choose n such that the cone angle equals the width of the peak of the third eclipse cycle (90°), we find a predicted light curve in agreement with observation. The radiation in the shoulder is severely depleted at energies below ~4 keV. The intensity in the peak is 60 percent of maximum. The missing 40 percent will be scattered by the ionized gas and will be redistributed in all directions. Much of this radiation will now reach us, even if in directions outside the ionized cone, since for a given angle it will traverse much less dense nonionized regions than the direct radiation from the star. We estimate that this contributes a DC level about 10 or 15 percent of peak value. The superposition of these effects accounts, at least qualitatively, for the shape and spectrum of the observed radiation. Furthermore, the monotonic increase in the pulsed fraction as the turn-on proceeds can be attributed to an increased percentage of unscattered intensity reaching us, due to the decrease in optical depth for Thomson scattering in the ionized region.

The nature of the other two observations, the 1973 February turnoff and possible 1972 March turn-on, cannot be explained in the same way. The lack of spikes and lack of significant spectral change during the 1973 February turnoff point toward a change in accretion rate, rather than a masking of the source. We estimate that a decrease in accretion by a factor of 20 would be sufficient to decrease the intensity to below detectable limits. This could be due to an increase in wind velocity by a small amount or by a decrease in density by a factor of 20. Thus we are led to a picture whereby the "normal" X-ray intensity level occurs for a limited range of stellar wind densities and possibly velocities. If the density of the stellar wind is too high, the source is effectively masked, with the energy reradiated at other wavelengths. Too little density, or too high a wind velocity, leads to a low level of emission.

The 1972 March data cannot be explained by either simply increasing the accretion rate or decreasing the wind density and thus the Thomson scattering. The increased low energy cutoff in the first cycle indicates more cold gas, but not enough to account for the entire intensity change. Furthermore, there is no significant change in either intensity or spectra between the second and third cycles. It is possible that the three cycles of data are not representative of a transition in the same sense as the previously discussed turn-on and turnoff.

In Cen X-3, dips are comparatively rare and erratic, compared with the regularly marching dips of Her X-1 (Giacconi *et al.* 1973) which are readily interpreted in a Roche lobe model as interaction of a cold mass stream with an accretion disk. In the 1972 March data, the two dips occurred prior to phase 0.5. In the 1972 July data, the dip was observed near phase 0.75. Furthermore, in 1972 September, a dip was observed near phase 0.75 of one binary period, but no obvious effect was seen in the adjacent period. The data thus suggest that the conditions necessary for the existence of dips may not always be present, and, furthermore, may be variable on a time scale of less than 2 days. The most obvious explanation of dips in Cen X-3 data invokes absorption by a high-density region produced by the stellar wind accretion wake (e.g., Davidson and Ostriker 1973; Illarionov and Sunyaev 1974).

The presence of dips before phase 0.5 might necessitate a large opening angle of the wake and increased absorption close to the leading shock front. However, it is not obvious that stellar wind accretion and an accretion disk are mutually exclusive. In fact, the speedup of the Cen X-3 pulsation period (Schreier *et al.* 1972; Gursky and Schreier 1974) indicates a significant amount of angular momentum transfer to the compact object; it is thus likely that an accretion disk exists. In this case, the dips may be explained, in analogy with Her X-1, by an interaction between the accretion disk and either a direct mass stream or the accretion wake infall.

A final consideration involves the persistence of X-ray emission in eclipse. The inefficient stellar wind accretion process leads to some 10^3 times more mass lost from the system compared with a Roche lobe overflow model with the same accretion rate. We thus consider that the radiation observed during eclipse may come from a shell of optically thin gas at some distance from the system. In order for the shell emission to persist during eclipses and perhaps over much longer periods, we require that either this shell be continuously heated at a level independent from the instantaneously observed X-ray luminosity or its cooling time be greater than 10^5 s. At the observed temperature of 10^7–10^8 K this requires a density of less than 10^{10} which is reached at a distance of 3×10^{12} cm from the primary star. The integrated emission from a shell with this inner radius and comparable thickness is of the order of 10^{36} ergs s^{-1}. Although this low-density gas could not be heated in steady state by the impinging X-rays, it might be heated in close proximity to the source and then expand to large distances in a time short compared with the bremsstrahlung or adiabatic cooling time. Alternatively, steady state heating by particles or shocks might be invoked. These ideas are consistent with several of the observations discussed. First, the lower temperature of the surrounding gas will produce X-rays with a significantly lower temperature than the primary noneclipsed X-rays. Second, the increased ratio of eclipse to noneclipse intensity during the extended lows ($\sim\frac{1}{2}$) compared with the normal states ($<1/10$) implies some degree of independence of the eclipse emission from the primary emission. The observations are thus more consistent with a cooling shell of gas at some distance than with, for example, scattering of the primary radiation by ionized gas in the umbra (e.g., see Davidson and Ostriker 1973).

We find the general model discussed to be in qualitative and often quantitative agreement with the observations. We thus conclude that just as Her X-1 provided a good model for Roche lobe mass transfer onto a neutron star from a low-mass companion, Cen X-3 demonstrates the existence of accretion onto a compact object from the stellar wind of a massive companion. It also opens interesting possibilities for the study of radiation driven winds in massive stars via X-ray observations.

NOTE.—After completion of the bulk of this work, the authors received preprints from K. A. Pounds, B. A. Cooke, M. J. Ricketts, M. J. Turner, and M. Elvis describing an extended Cen X-3 observation with *Ariel-5*; from J. C. Jackson interpreting the

Ariel-5 observations; and from I. R. Tuohy and A. M. Cruise discussing a *Copernicus* observation of Cen X-3. We find these papers confirming, in a general way, the behavior of Cen X-3 here described and also the erratic nature of the dips. We find the model for an intensity transition described by Jackson to be incompatible with much of our data.

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REFERENCES

Bahcall, J. N., and Bahcall, N. A. 1972, *Ap. J.* (*Letters*), **178**, L1.
Baity, W. A., Ulmer, M. P., Wheaton, W. A., and Peterson, L. E. 1974, *Ap. J.*, **187**, 341.
Davidsen, A., Henry, J. P., Middleditch, J., and Smith, H. 1972, *Ap. J.* (*Letters*), **177**, L97.
Davidson, K., and Ostriker, J. P. 1973, *Ap. J.*, **179**, 585.
Forman, W., Jones, C. A., and Liller, W. 1972, *Ap. J.* (*Letters*), **177**, L103.
Giacconi, R. 1974, Seventh Texas Symposium on Relativistic Astrophysics.
Giacconi, R., Gursky, H., Kellogg, E. M., Levinson, R., Schreier, E., and Tananbaum, H. 1973, *Ap. J.*, **184**, 227.
Giacconi, R., Gursky, H., Kellogg, E. M., Schreier, E., and Tananbaum, H. 1971, *Ap. J.* (*Letters*), **167**, L67.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E. M., Schreier, E., Matilsky, T., Koch, D., and Tananbaum, H. 1974, *Ap. J. Suppl.*, No. 237, **27**, 37.
Gursky, H., and Schreier, E. 1974, *IAU Symposium No. 67*, Moscow, USSR.
Illarionov, A. F., and Sunyaev, R. A. 1974, Academy of Sciences of the USSR, Space Research Institute, preprint 202.
Joss, P. 1974, private communication and Seventh Texas Symposium on Relativistic Astrophysics.
Krzeminski, W. 1974, *Ap. J.* (*Letters*), **192**, L135.
Margon, B., Bowyer, S., Lampton, M., and Cruddace, R. 1972, *Nature Phys. Sci.*, **237**, 104.
Margon, B., Lampton, M., Bowyer, S., and Cruddace, R. 1975, *Ap. J.*, **197**, 25.
McCray, R. 1974, International Conference on X-rays in Space, Calgary, Alberta, Canada.
Pines, D., Pethick, C. J., and Lamb, F. K. 1972, Sixth Texas Symposium on Relativistic Astrophysics.
Pounds, K. 1974, Seventh Texas Symposium on Relativistic Astrophysics.
Pringle, J. E. 1973, *Nature Phys. Sci.*, **243**, 90.
Rickard, J. J. 1974, *Ap. J.* (*Letters*), **189**, L113.
Schreier, E., Levinson, R., Gursky, H., Kellogg, E. M., Tananbaum, H., and Giacconi, R. 1972, *Ap. J.* (*Letters*), **172**, L79.
Tananbaum, H., Gursky, H., Kellogg, E. M., Levinson, R., Schreier, E., and Giacconi, R. 1972, *Ap. J.* (*Letters*), **174**, L143.
Van den Heuvel, E., and Heise, J. 1972, *Nature*, **239**, 67.
Vidal, N. V., Wickramasinghe, D. T., Peterson, B. A., and Bessell, M. S. 1974, *Ap. J.* (*Letters*), **191**, L23.

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